ANALYSIS OF ENERGY SAVING POTENTIAL AND OPTIMIZATION OF THERMALLY BROKEN FIBERGLASS WINDOW FRAMES

Jan Zajas, Per Heiselberg
Department of Civil Engineering, Aalborg University
9000 Aalborg, Denmark

ABSTRACT
This paper elaborates on the energy saving potential and development process of fiberglass window frames, with intention for application in cold climates. A method is presented, where different means of improving thermal performance of a window frame are evaluated. Firstly, very simple geometries are considered, as a simple benchmark for various investigations. Further on, the complexity is gradually increased.

Various means of diminishing the heat flow are evaluated. Results show that large improvement can be obtained, when cavities are subdivided by vertical walls or filled with insulation. U value of a window frame can be significantly reduced by these means.

Performance of an actual fiberglass frame optimized in this work is significantly improved, but still not competitive against state of the art frames. This indicates that more drastic improvements need to be done in order to achieve satisfying results.

INTRODUCTION
Space heating contributes to approximately 50% of the total energy consumption of a building (Lautsen 2008). This number can be significantly reduced by providing better thermal insulation to diminish transmission losses through the building envelope.

Window frames have usually been considered as the “weakest link” and even though they cover a relatively small fraction of the envelope area, they are still responsible for a significant amount of heat loss (Byars et al. 1990). This weakness became even more clear in recent years, as the insulation properties of glazing have been greatly improved, what allows them to reach much lower U values than that of the frames. This problem can be handled by designing window frames with improved thermal performance.

Choosing the right material however, does not ensure satisfying thermal properties of a window frame. To obtain a low U value, design of the frame needs to be optimized in regard of thermal properties. Previous research focused mostly on developing slim frames to minimize fraction of frame area in the entire window (Lautsen et al., 2005, Appelfield et al., 2010). Buildings with such windows can benefit from higher solar heat gains, due to increased glazing area. Little work has been put however, into investigations of how U value of the frame itself can be lowered.

Several means can be taken in order to reduce the heat loss through the frame. Modern window frames made of vinyl, fiberglass or aluminum usually have several hollow cavities inside. In such case, total heat transfer through a frame consists of:

- Conduction through solid materials.
- Convection and radiation through the cavities.

Each of these means of heat transfer can be diminished in certain ways.

One of the ways to reduce heat conduction in the structural walls of the frame can be to embed a layer of insulation inside the frame walls. Various insulation materials can have thermal conductivity up to ten times lower than fiberglass, therefore this might have a major impact on thermal performance.

Several steps can be taken to diminish heat transfer in the cavities. Radiation effects can be reduced by using materials with low emissivity. Oxidized aluminum can be used for this purpose.

To reduce convective heat transfer, a cavity can be subdivided into smaller chambers. If size of the cavity is small enough, the air enclosed in it can act as a good insulation, due to limited air circulation inside.

Finally, the cavity can be completely filled with insulation. This solution can deliver good results but also might be more costly to implement.

In the present study, it is investigated how each of the methods to diminish heat transfer mentioned above can help improve the window frames. Firstly, simple geometries are taken into consideration, to give a better understanding of the principles that govern heat transfer in window frames. After that, an actual
frame made of fiberglass is considered. It is investigated how different solutions can help to improve its thermal performance. Finally it is calculated how the frame can perform when integrated in a window.

This paper will explain the numerical procedure used for deriving the thermal transmittance of the frame. Geometries used in the study will be presented and the impact of various means of reducing heat transfer will be analyzed and discussed.

METHODS

Development method

Figure below presents the idea behind the investigation presented in this paper.

![Figure 1: Sketch of the development method.](image)

Firstly very simple geometries will be considered. It will be analysed how thermal performance can be improved, by placing insulation, dividing cavities, etc. Gradually, more complex geometries will be analysed, with knowledge from the previous investigations being used in next stages for the benefit of improving the insulation properties.

Numerical procedure

As mentioned before, heat transfer through the window frame is a combination of conduction, convection and radiation. Conduction can be simply modelled with Finite Element Method (FEM) simulations. Two other means of heat transfer are more difficult to predict and require more sophisticated methods.

In most of the previous work in window frame research, simplified solutions were used to calculate the heat transfer (Lautsen et al., 2005, Appelfield et al., 2010). Those methods are based on treating the cavities as solid materials with effective thermal conductivity, as described in international standards ISO 10077 and 10599. Studies made by Gustavsen et al. (2001) show however, that better agreement between simulations and reality is obtained when more detailed algorithms are used. This includes fluid flow simulations for solving convective heat transfer and view factor methods for describing radiation effects.

In this study, a Finite Element Simulation tool (COMSOL Multiphysics) is used to calculate the thermal transmittance. Fluid flow simulations are conducted to estimate the convective heat transfer. Rayleigh number was calculated in order to determine the nature of the flow inside the cavities:

\[
Ra = \frac{\rho_{\text{air}} \cdot \beta_{\text{air}} \cdot g \cdot c_{p,\text{air}} (T_H - T_C)}{\lambda_{\text{air}}} \tag{1}
\]

The highest Rayleigh number found in this study was approximately 1.9 \times 10^6. Arpino et al., (2010) reports laminar flow for this value. Incompressible flow is also assumed.

For radiative heat transfer, the hemicube method is used to evaluate view factors. It uses a z-buffered projection on the sides of a hemicube (with generalizations to 2D and 1D) to account for shadowing effects.

Only 2 dimensional simulations are conducted in order to reduce the complexity.

Several factors are calculated in order to evaluate the performance of the frame. Below a brief explanation of them is presented.

\[ U \text{ value of the frame (} U_f \text{)} \]

It is calculated according to methodology described in ISO 10077-2: simulations are conducted in the absence of glazing, which is substituted by an insulating panel. Thus, the effect of glazing and spacer on the \( U \) value is removed.

\[ \text{Linear thermal transmittance (} \Psi \text{)} \]

This value describes the effect of glazing and spacer on the overall heat transfer. To derive it, a separate simulation is conducted with glazing and the spacer placed instead of an insulating panel. A simplified spacer shape with an equivalent conductivity is used. Glazing used in the simulations is triple glazing with Argon filling.

\[ U \text{ value of the entire window (} U_w \text{)} \]

It is calculated according to ISO 10077-2 standard. It includes heat transfer through the window frame, the glazing and additional linear heat loss caused by assembly of frame and glass.

\[
U_w = \frac{U_g \cdot A_g + U_f \cdot A_f + \Psi \cdot l_p}{A_g + A_f} \tag{2}
\]

Standard window size of 1.23 \times 1.48 m is used. Window with \( U_g=0.71 \text{ W/m}^2\text{K} \) and \( g=0.57 \) was chosen.

\[ \text{Net Energy Gain Factor (NEG)} \]

This factor evaluates energy performance of the entire window during a standard heating season. It is described as the solar heat gains subtracted from the transmission heat losses. If the NEG factor has a positive value, it indicates that the window is contributing to heating of the building. It is described by the formula below:

\[
NEG = g \cdot I - U_w \cdot D \tag{3}
\]

Where \( I \) and \( D \) are coefficients for heat gain and heat loss respectively. They are dependent on the location and for Denmark they have been calculated to be equal to \( I=196.4 \text{ kWh/m}^2\text{K} \) and \( D=90.36 \text{ kKh} \). (Nielsen et al., 2009).
MATERIAL PROPERTIES
Not all materials are suitable for window frame market. One of the qualities that such material should meet is sufficient load carrying capabilities. Moreover, thermal conductivity is important. Other factors, like durability or maintenance and production cost should be also taken into consideration. Because of these strict requirements, only few materials are commonly used as structure of window frames. A summary and comparison between most common materials is presented in table 1.

Fiberglass does not peak in any category, but shows satisfying properties in all of the areas of interest. Its thermal conductivity is very close to that of wood and PVC. In structural properties, it performs almost as well as aluminium. Moreover, the costs over its life cycle are low, due to the low energy consumption during production and a long lifespan. Also, fiberglass allows for a large freedom of design, since it can be pultruded into almost any shape.

Materials used for window frames include not only structural components, but also weather stripping, spacers etc. Table 2 shows the properties of materials used in the simulations.

Aluminium is used in this work as a thermal break against radiative heat transfer. Its low emissivity makes it a suitable material for this application. However, emissivity of a material can be affected by aging and dirtiness of the surface. A discussion on this topic was made by Gustavsen et al, (2003).

Studies show that new profiles can have emissivity even as low as 0.04. Over time, aluminium can grow an oxide layer that will increase this number. A value of 0.2 is normally used in window frame research and represents aluminium after several years of being in use. This approximation seems safe to be used also in this study.

Air properties used in simulations vary in function of temperature and pressure and are calculated by the simulation program.

BOUNDARY CONDITIONS
Table 3 presents boundary conditions used for various simulations. For the first geometry constant temperatures are set on both side of the analysed profile, thus the surface heat transfer coefficient equals infinity. For window frames, coefficients are set according to the standards. A gravitational force of 9.81 m/s² was used in the calculations.

GEOMETRIES
Geometry 1: fiberglass wall.
Firstly, a simple study is made, which can help investigate how thermal conductivity of fiberglass walls might be improved, when a layer of insulation is embedded into it. Geometry for this case is shown on figure 2a. It represents a typical window frame wall. Thickness is equals to 3 mm, which is a common dimension in fiberglass frames.

Fiberglass window frames are usually composed of several rectangular cavities, surrounded by vertical and horizontal walls, through which the heat is being conducted. To analyse how heat transfer can be diminished in both of these situations two cases are considered:

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**Table 1**

<table>
<thead>
<tr>
<th>PROPERTY</th>
<th>ALUMINUM</th>
<th>PVC</th>
<th>WOOD</th>
<th>FIBERGLASS</th>
</tr>
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<tbody>
<tr>
<td>Tensile strength [Mpa]</td>
<td>300</td>
<td>30</td>
<td>14</td>
<td>240</td>
</tr>
<tr>
<td>E-modulus [Gpa]</td>
<td>72</td>
<td>3</td>
<td>7</td>
<td>23</td>
</tr>
<tr>
<td>Thermal conductivity [W/mK]</td>
<td>160</td>
<td>0.17</td>
<td>0.13</td>
<td>0.30</td>
</tr>
<tr>
<td>Suitable for larger structures</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Energy consumption during production</td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
<td>Low</td>
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<tr>
<td>Maintenance cost</td>
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<td>Low</td>
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<td>Low</td>
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<tr>
<td>Life span</td>
<td>Long</td>
<td>Medium</td>
<td>Short</td>
<td>Long</td>
</tr>
</tbody>
</table>

**Table 2**

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>THERMAL CONDUCTIVITY [W/mK]</th>
<th>EMMISIVITY [-]</th>
</tr>
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<tbody>
<tr>
<td>Fiberglass</td>
<td>0.3</td>
<td>0.9</td>
</tr>
<tr>
<td>Insulation</td>
<td>0.04</td>
<td>0.9</td>
</tr>
<tr>
<td>Aluminium</td>
<td>160</td>
<td>0.2</td>
</tr>
<tr>
<td>Softwood</td>
<td>0.11</td>
<td>0.9</td>
</tr>
<tr>
<td>EPDM</td>
<td>0.25</td>
<td>0.9</td>
</tr>
<tr>
<td>Insulation panel</td>
<td>0.035</td>
<td>0.9</td>
</tr>
<tr>
<td>Spacer</td>
<td>0.18</td>
<td>0.9</td>
</tr>
<tr>
<td>Polysulphide</td>
<td>0.4</td>
<td>0.9</td>
</tr>
<tr>
<td>Glazing cavity</td>
<td>0.02</td>
<td>-</td>
</tr>
<tr>
<td>Glass</td>
<td>1</td>
<td>-</td>
</tr>
</tbody>
</table>

**Table 3**

<table>
<thead>
<tr>
<th>NAME</th>
<th>TEMPERATURE T [°C]</th>
<th>HEAT TRANSFER COEFFICIENT [W/mK]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outdoor</td>
<td>0</td>
<td>Infinity* / 25**</td>
</tr>
<tr>
<td>Indoor</td>
<td>20</td>
<td>Infinity* / 7**</td>
</tr>
</tbody>
</table>

* - geometry 1, ** - geometries 2 and 3

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- 698 -
a) Heat flow from right to left – representing horizontal walls of the frame.
b) Heat flow from top to bottom– representing vertical walls of the frame.

A value of effective heat conductivity is derived for the assembly of fiberglass/insulation.

**Geometry 2: hypothetical frame.**
Further investigation is done with a more complex geometry. A hypothetical frame with triple glazing is considered. Dimensions are as shown on figure 2b. The frame is composed of a large inner cavity, which can be divided into multiple smaller chambers. A parametric geometry is created, which allows to quickly change many variables, like number of horizontal or vertical divisions or wall thickness. Multiple cases with various amounts of subdivisions are considered in this study. Additionally, insulation layers are placed in the fiberglass walls in some of the simulations. The results from previous investigation are used to determine the optimal shape and amount of the insulation.

**Geometry 3: actual window frame.**
Finally, an actual frame is considered. It is a fiberglass inward opening frame with wooden cladding on the inside. The geometry is slightly simplified, as shown on figure 3. There are several reasons behind these modifications. First of all, size of the large cavity in the middle of the frame is reduced drastically. This particular cavity allows the frame to open and close, therefore there are limited options for modifying it, i.e. it cannot be filled with insulation or subdivided into smaller chambers. It is decided to reduce it and to use the acquired space to increase the size of the cavities below and above it, which can be modified freely in the further investigation. Also, the two cavities on the top are joined together so that more space for modifications is obtained there.

Figure 2c. shows detailed geometry. Also, it indicates how cavities are modified in further stage. Cavity in the middle and below glazing cannot be fully closed by the partition walls. Therefore some space is left, so that the frame can operate normally. Other large cavities are either subdivided by partition walls or filled with insulation, as shown on the figure. Remaining cavities are of too small size and no alterations are made in them.

**Figure 3: Simplification of the actual window frame**

**RESULTS**

**Geometry 1.**
Figure 4. presents the results for a horizontal wall. The horizontal axis shows relative thickness of insulation layer in the entire profile. The vertical axis presents the effective thermal conductivity of the assembly of fiberglass and insulation. The different curves plotted on the graph represent various relative widths of the insulation.

It can be seen that introduction of insulation layer has a positive effect on thermal performance. Increasing the dimensions of the insulation gives a steady improvement in the thermal resistance of the material. However, there needs to be some restraint, so that mechanical properties are not worsened too drastically. Firstly it should be determined which of the two dimensions has a larger impact on the output. By looking at the results it can be concluded that, in this case, thickness of the insulation is a more important factor. Width is a secondary parameter in this situation. Between relative widths of 0.2-0.6 a clear difference can be seen, but for larger values the curves are almost overlapping. It is decided therefore, that a width of 0.5 is a reasonable choice to be used in further studies. For the thickness, fraction of 0.5 is chosen as well. Dashed lines on the graph indicate the resultant thermal conductivity for these dimensions. It is equal to 0.217 W/mK.

Figure 5 presents results for the vertical wall. Dependence between the dimensions of insulation
and thermal conductivity is very different compared to previous situation. A large difference exists between various curves, what indicates that width of the insulation is the key factor in this case. Thickness, on the other hand, is not extremely important. The dependence between conductivity and thickness resembles a logarithmic function. There is a large drop in the thermal conductivity, when relative thickness is increased from 0 to 0.5. Further on, the curve levels out and little improvement can be seen.

It can be concluded, that in this case insulation layer should be as wide as possible, preferably covering almost the entire cross-section. It is decided that in next investigations a relative width of 0.9 and thickness of 0.33 is to be used. With such dimensions of the insulation layer, the thermal conductivity is reduced to 0.116 W/mK.

This simple investigation gives some insight on where the insulation should be applied and what shape should it take. It indicates that insulating vertical walls might have larger significance, as much lower thermal conductivity has been reached for this direction of heat flow.

Also, it should be kept in mind that this consideration presents an ideal situation where heat is flowing only from one side of the geometry to another. In reality, the nature of heat flow can be much more complex and the results might differ.

**Geometry 2: hypothetical frame.**

With the use of this geometry it can be investigated how and to what extent the convective and radiative heat transfer in cavities of the frame can be limited.

In general, subdividing the cavities limits the air movement inside and helps reduce the convective heat transfer. Additionally, vertical walls can diminish radiative heat flux.

Several situations are considered. The main cavity is divided either horizontally or vertically and up to 10 partition walls are placed. Fiberglass and aluminium are used as material for the walls.

Another investigation is conducted with insulation layers placed in fiberglass walls. It is also examined how reduction of thickness of the walls can contribute to improving the frame.

Figure 6 presents results for horizontal and vertical subdivisions. Dividing the frame horizontally shows some improvement, but only to a certain point. With number of divisions higher than 6, the U value starts to increase. At this point horizontal walls act as thermal bridges, as they conduct more heat than the air enclosed between them.

Subdividing the frame vertically provides more satisfying results. U value can be reduced by nearly 60% when 5 subdivisions are placed. With higher amount of partitions, little or no improvement can be seen.

Even larger improvement can be achieved when aluminium walls are placed inside. Fewer divisions are needed to obtain a low U value – with only 3 walls total transmittance is lowered by 66%. This indicates that large share of heat transfer through a window frame is by means of radiation. As more subdivisions are placed, U value starts to rise, what is caused by large thermal conductivity of aluminium.

Figure 7 shows how the result for horizontal subdivisions can be further improved when some changes to the walls are introduced. Two situations are considered. Firstly, insulation layers are placed within the walls. Dimensioning of the insulation layers is done according to results from previous geometry.

Some improvement can be seen, but mostly for higher amount of subdivisions. For 3 or less partitions there is hardly any change in the U value.

Very similar results are obtained when thickness of the walls is reduced by 50% instead of placing insulation. At the same time this solution is easier to implement in the production process and therefore will be considered in next stages instead. It should be also noted, that, in a way, these two solutions work on the same principle. Whether it is reducing the thickness the frame or including insulation, some amount of fiberglass is removed, thus limiting the conductive heat transfer.

Another factor that should be considered is the influence of these solutions on mechanical properties of the frame. Including an insulation layer creates a
sandwich construction, which probably has a higher strength than the thin wall.

Figure 8 presents result for vertical walls. Again, with insulation placed inside the walls, U value is slightly reduced. Changing the thickness does not lead to a large improvement and is not an optimal solution in this case.

Additionally, it is considered if combining vertical and horizontal subdivisions can contribute to decreasing the U value. Figure 9 presents results for this situation. It can be seen that small improvement is obtained for low numbers of subdivisions. For higher numbers, presence of horizontal walls becomes a drawback, as U value becomes larger.

Last simulation was run for a frame with a cavity completely filled with insulation. A U value of 0.80 W/m²K was achieved. The best result obtained from subdividing cavities is 0.94 W/m²K, when aluminium partitions are used.

Geometry 3: actual window frame.

In this part it is investigated how the solutions developed in previous subsections can be used in reality and help to improve an actual frame. Again, several cases are considered. Figure 10 presents the results. Firstly a frame with empty cavities is simulated. This results in a U value of 2.05 W/m²K. Such a frame provides very poor insulation and is not acceptable in modern low energy buildings.

Secondly, the frame is divided vertically. Four fiberglass walls are placed in all large cavities. Significant improvement can be observed as the U value is reduced to 1.46.

In the next step, thickness of all horizontal walls is reduced by 50% as it was done in previous simulations. Further improvement can be seen when this solution is implemented. Furthermore, insulation is embedded in each vertical wall. After all these modifications, U value is brought down to 1.24 W/m²K, what is a significant decrease compared to the first stage.

Vertical aluminium subdivisions are used in next consideration. In this case horizontal walls are also thinner. Even better result is obtained in this case, as U value is decreased by over 40% compared to the first stage.

Finally, a situation with cavities completely filled with insulation is considered. A U value of 1.13 W/m²K is obtained, almost identical to the case with aluminium subdivisions.
Energy performance of the entire window.

In this final investigation, it is evaluated how frames considered in this chapter can perform when installed in a window. Data for this investigation is gathered in Table 4. Calculations include derivations of \( U \) values of entire window and the net energy gain factors.

“Unoptimized” stands for a frame with hollow cavities. “Optimized” is the best solution obtained in previous stage – a frame with cavities filled with insulation. Reference frame is a PassivHaus certified frame made of PVC and aluminium.

When unoptimized frame is integrated with a window, \( U_w \) of 1.23 is obtained. Large improvement can be seen for optimized frame, as the \( U_w \) value is decreased by almost 25%. NEG factor changes drastically as well, what shows that large amount of energy can be saved when using the optimized frame.

In both cases however, this value is negative. This means that transmission losses are higher than solar heat gains generated by the window.

In comparison to the reference frame, optimized frame does not prove to be very competitive. \( U \) value for both the frame and entire window are higher. Further work needs to be done in order to lower the \( U \) value even more. Perhaps more drastic modifications to the design of the frame need to be done.

CONCLUSIONS

Several ways of improving thermal performance of a window frame have been considered. It was found that subdividing the cavities by vertical walls can have a large positive impact on the \( U_f \) value. Additional improvement can be achieved when insulation is placed within the walls or when their thickness is reduced.

This study also proved that aluminium can act as a good thermal breaker, even though its thermal conductivity is significantly larger than the one’s of fiberglass. When used properly, it can perform almost as well as insulation.

Simulation on an actual frame show that solutions developed in this study can lower \( U \) value of a frame and increase the energy savings, but only to a certain point. A more radical approach needs to be taken in order to surpass state of the art frames made of other materials. Optimization of an existing frame is not a sufficient measure. A method for designing a highly insulated window frame from scratch, with an emphasis on its insulation properties should be developed and might be a part of future work.

![Figure 10: U value of the frame in different cases](image-url)

### Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
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<tbody>
<tr>
<td>( FEM )</td>
<td>Finite Element Method</td>
<td></td>
</tr>
<tr>
<td>( Ra )</td>
<td>Rayleigh number [-]</td>
<td></td>
</tr>
<tr>
<td>( \rho )</td>
<td>Density ([\text{kg/m}^3])</td>
<td></td>
</tr>
<tr>
<td>( L_h )</td>
<td>Length scale ([\text{m}])</td>
<td></td>
</tr>
<tr>
<td>( g )</td>
<td>Acceleration of gravity ([\text{m/s}^2])</td>
<td></td>
</tr>
<tr>
<td>( \beta )</td>
<td>Coefficient of thermal expansion ([1/\text{K}])</td>
<td></td>
</tr>
<tr>
<td>( c_p )</td>
<td>Specific heat of air ([\text{J/kg K}])</td>
<td></td>
</tr>
<tr>
<td>( T_H )</td>
<td>Temperature of the hot side ([\text{K}])</td>
<td></td>
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<tr>
<td>( T_C )</td>
<td>Temperature of the cold side ([\text{K}])</td>
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</tr>
<tr>
<td>( \mu )</td>
<td>Dynamic viscosity ([\text{Pa s}])</td>
<td></td>
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<tr>
<td>( \lambda )</td>
<td>Thermal conductivity ([\text{W/m K}])</td>
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</tr>
<tr>
<td>( U_f )</td>
<td>U value of the frame ([\text{W/m}^2\text{K}])</td>
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</tr>
<tr>
<td>( U_g )</td>
<td>U value of the glazing ([\text{W/m}^2\text{K}])</td>
<td></td>
</tr>
<tr>
<td>( U_w )</td>
<td>U value of the entire window ([\text{W/m}^2\text{K}])</td>
<td></td>
</tr>
<tr>
<td>( A_k )</td>
<td>Area of the glazing ([\text{m}^2])</td>
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</tr>
<tr>
<td>( A_f )</td>
<td>Area of the frame ([\text{m}^2])</td>
<td></td>
</tr>
<tr>
<td>( g )</td>
<td>Solar heat gain coefficient [-]</td>
<td></td>
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<tr>
<td>( \Psi )</td>
<td>Linear thermal transmittance ([\text{W/mK}])</td>
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<tr>
<td>( l_p )</td>
<td>Perimeter of glazing ([\text{m}])</td>
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<td>Net energy gain factor ([\text{kWh/m}^2\text{ year}])</td>
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<td>( D )</td>
<td>Coefficient for heat loss ([\text{kKh}])</td>
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